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# The Spatiotemporal Dynamics of Vegetation Cover and Its Response to the Grain for Green Project in the Loess Plateau of China

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**Abstract:** The Grain for Green Project (GGP) is a major national initiative aimed at ecological improvement and vegetation restoration in China, achieving substantial ecological and socio-economic benefits. Nevertheless, research on vegetation cover trends and the long-term restoration efficacy of the GGP in the Loess Plateau remains limited. This study examines the temporal–spatial evolution and sustainability of vegetation cover in this region, using NDVI data from Landsat (2000–2022) with medium-high spatial resolution. The analytical methods involve Sen's slope, Mann–Kendall non-parametric test, and Hurst exponent to assess trends and forecast sustainability. The findings reveal that between 2000 and 2022, vegetation coverage in the Loess Plateau increased by an average of 0.86% per year ($p < 0.01$), marked by high vegetation cover expansion ($173 \times 10^3$ km$^2$, 26.49%) and low vegetation cover reduction ($149 \times 10^3$ km$^2$, 22.83%). The spatial pattern exhibited a northwest-to-southeast gradient, with a transition from low to high coverage levels, reflecting a persistent increase in high vegetation cover and decrease in low vegetation cover. Approximately 93% of the vegetation cover in the Loess Plateau showed significant improvement, while 5% (approximately $31 \times 10^3$ km$^2$) displayed a degradation trend, mainly in the urbanized and Yellow River Basin regions. Projections suggest that 90% of vegetation cover will continue to improve. In GGP-targeted areas, high and medium-high levels of vegetation cover increased significantly at rates of $0.456 \times 10^3$ km$^2$/year and $0.304 \times 10^3$ km$^2$/year, respectively, with approximately 75% of vegetation cover levels exhibiting positive trends. This study reveals the effectiveness of the GGP in promoting vegetation restoration in the Loess Plateau, offering valuable insights for vegetation recovery research and policy implementation in other ecologically fragile regions.

**Keywords:** vegetation coverage; trend analysis; vegetation restoration; Grain for Green Project; Loess Plateau

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## 1. Introduction

The Loess Plateau ranks among the most severely eroded regions both in China and globally [1]. Human activities, including deforestation and overgrazing, have intensified soil erosion and ecological imbalances, leading to extensive vegetation degradation and severe environmental harm, which present ongoing challenges for future generations [2,3]. In response to deteriorating environmental conditions, significant land degradation, and advancing academic perspectives on ecosystem services, the Chinese government launched the large-scale GGP in 1999 as an ecological restoration strategy. This project seeks to enhance the environment and promote regional sustainable development through vegetation restoration [4]. Vegetation serves as a crucial indicator of ecological changes and is notably impacted by human activities [5]. Investigating the spatiotemporal characteristics and

trends of vegetation cover changes under the GGP holds considerable practical significance for understanding the mechanisms and impacts of ecological restoration in the Loess Plateau [6,7].

NDVI is a commonly used index for monitoring vegetation growth status in remote sensing studies of vegetation changes [8,9]. FVC emphasizes quantitative vegetation coverage assessment and is widely utilized in ecological environment assessments and evaluations of vegetation restoration effectiveness [10,11]. Both NDVI and FVC are closely linked to vegetation characteristics and conditions, serving as essential indicators for assessing vegetation status and distribution [12,13]. Scholars have applied methods such as transition matrices [14], centroid migration models [15], stability analysis, and trend analysis to uncover the dynamic characteristics and patterns of vegetation coverage in spatiotemporal vegetation studies [16]. In trend analysis, combining the Theil–Sen slope and Mann–Kendall test facilitates identifying vegetation recovery from long-term remote sensing data [17], elucidating potential recovery capacities. Time-series NDVI data from sources such as GIMMS, SPOT-VGT, and MODIS are extensively employed in analyzing vegetation cover's spatiotemporal changes and trends. GIMMS data offer a long time series of NDVI from 1982 to 2015. However, due to limitations in satellite sensors and data processing, its spatial resolution is relatively low (8 km × 8 km), restricting its ability to capture small-scale ecological changes and exhibiting noise and inconsistencies [18]. SPOT-VGT data provide wider coverage, higher temporal resolution, and enhanced spatial resolution at 1 km, although sensor changes lead to continuity and reliability challenges [19]. MODIS offers vegetation product data with spatial resolutions of 250 m, 500 m, and 1000 m [20–22], delivering NDVI data with long-term, high temporal resolution [23]. However, its spatial resolution is moderate, restricting its use in small-scale vegetation monitoring [24]. Variations in spatiotemporal resolution and quality among different vegetation dynamics datasets may lead to inconsistencies in vegetation change results [25]. Large-scale studies reveal significant discrepancies in vegetation monitoring among remote sensing data products. For instance, GIMMS displays higher NDVI values but shows smaller trend changes relative to SPOT-VGT and MODIS [26]. Although scholars have employed MODIS data to investigate the spatiotemporal characteristics of vegetation cover in the Loess Plateau, limited research has utilized annual 30 m spatial resolution Landsat NDVI time-series data to assess the effectiveness of vegetation restoration under the GGP in this region.

This study employs annual, high-spatial-resolution NDVI data from Landsat (2000–2022) to examine spatiotemporal patterns and classifications of vegetation cover in the Loess Plateau. The objective is to clarify the trends and sustainability of vegetation cover changes, assessing the GGP's impact on the spatiotemporal changes in vegetation cover. Specifically, this study quantitatively analyzes vegetation cover trends in the Loess Plateau, examining area variations in different levels of vegetation coverage to elucidate the type and extent of vegetation cover changes and vegetation recovery after the implementation of the GGP. The findings carry significant implications for enhancing ecological conditions, climate regulation, and biodiversity conservation. Additionally, this study provides a scientific reference for vegetation restoration and sustainable ecological development in other ecologically sensitive regions.

## 2. Materials and Methods

### 2.1. Study Area

The Loess Plateau is situated in northwestern China, between 33°41′ and 41°16′ N, and 100°51′ and 114°32′ E (Figure 1). Bordered by the Taihang Mountains to the west, Riyue Mountain in Qinghai Province to the east, the Qinling Mountains to the north, and the Yin Mountains to the south. Covering approximately 64 × $10^4$ $km^2$, the Loess Plateau has elevations ranging from 95 to 4900 m. This region experiences a temperate continental monsoon climate, with an average annual temperature between 2.2 °C and 13 °C and precipitation of 200 mm to 750 mm. Over 70% of annual rainfall is concentrated in the summer months. The topography features significant undulations, with a general

slope from the northwest to the southeast. The major geomorphological features consist of tablelands, ridges, and hills. As an ecologically fragile region, the Loess Plateau experienced extensive land reclamation in its early history, resulting in severe vegetation degradation from over-cultivation. The region's loose, erosion-prone soils, coupled with concentrated and highly variable rainfall, have led to significant soil erosion from the loss of protective vegetation and soil stability [27]. Before the implementation of the GGP, vegetation growth in the Loess Plateau was relatively slow. Since the project's inception in 1999, a vast area of cropland in the Yellow River Basin, particularly in the central Loess Plateau, has been converted to forest and grassland, significantly enhancing the ecological environment [28]. Consequently, studying vegetation recovery in the Loess Plateau is essential for soil erosion control and ecological restoration.

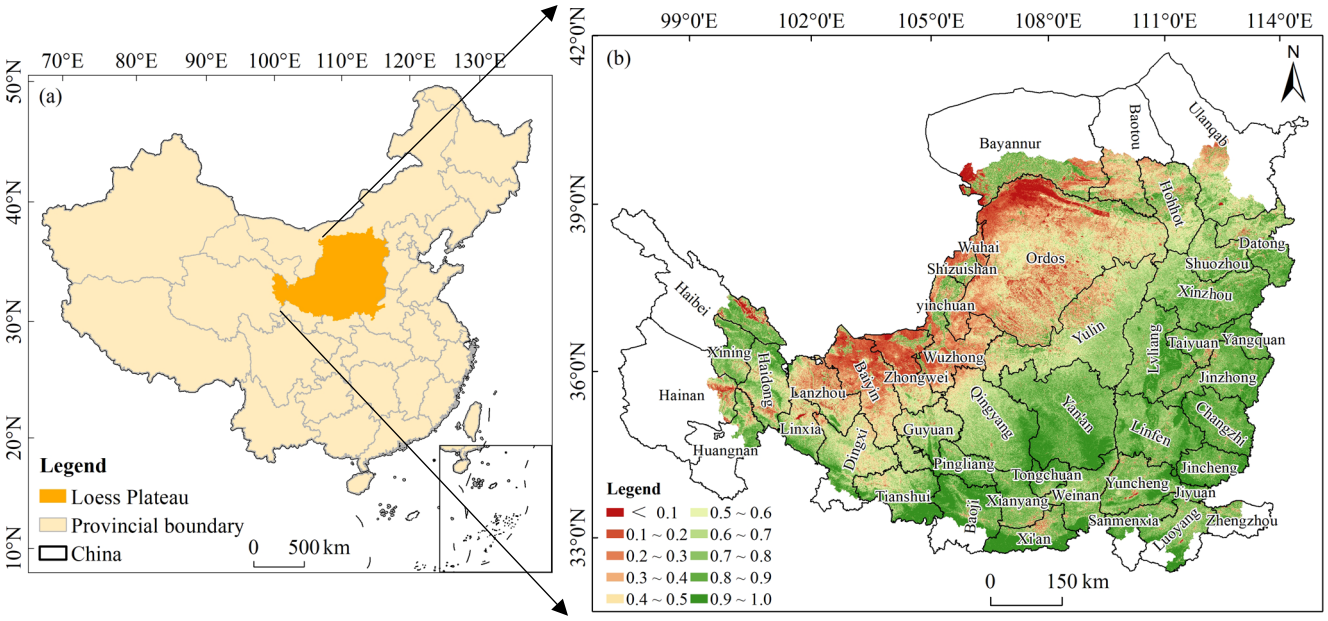



**Figure 1.** Overview of the study area. (**a**) shows the geographical location of the Loess Plateau in China, while (**b**) illustrates the spatial distribution of NDVI in the Loess Plateau for the year 2022. The NDVI values are categorized into 10 levels, where values closer to 1 indicate healthier vegetation conditions.

### *2.2. Data Sources and Processing*

NDVI data from 2000 to 2022 were sourced from a dataset provided by the Remote Sensing Team at the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences. This dataset was processed using Landsat 5/7/8/9 remote sensing data on the Google Earth Engine platform, featuring a 30 m spatial resolution and annual temporal resolution. The TIFF-formatted data are appropriate for representing vegetation growth conditions and calculating vegetation coverage [29]. For this study, the data were downloaded from the National Ecosystem Science Data Center (http://www.nesdc.org.cn, accessed on 3 July 2024) and clipped to the study area to acquire annual NDVI data for the Loess Plateau from 2000 to 2022. Land cover data from 2000 to 2022 with a 30 m spatial resolution were obtained from the CLCD published by Wuhan University. These data were processed and accessed through the Google Earth Engine platform [30]. Using land cover data from 2000 and 2022, the spatial distribution of the GGP areas was determined via the transition matrix method.

All abbreviations in the paper are listed in Table 1.

**Table 1.** List of abbreviations.

| Serial Number | Abbreviation | Full Name |
|---|---|---|
| 1 | GGP | Grain for Green Project |
| 2 | NDVI | Normalized Difference Vegetation Index |
| 3 | FVC | Fractional Vegetation Cover |
| 4 | GIMMS | Global Inventory Modeling and Mapping Studies |
| 5 | SPOT-VGT | SPOT Vegetation |
| 6 | MODIS | Moderate-resolution Imaging Spectroradiometer |
| 7 | CLCD | China Land Cover Dataset |
| 8 | L | Low coverage |
| 9 | ML | Medium-low coverage |
| 10 | M | Medium coverage |
| 11 | MH | Medium-high coverage |
| 12 | H | High coverage |
| 13 | R/S | Rescaled Range |
| 14 | Si-i | Significant improvement |
| 15 | Sl-i | Slightly improvement |
| 16 | B-u | Basically unchanged |
| 17 | Sl-d | Slightly degradation |
| 18 | Si-d | Significant degradation |
| 19 | S-si-i | Sustained significant improvement |
| 20 | S-sl-i | Sustained slight improvement |
| 21 | S-s | Sustained stability |
| 22 | S-sl-d | Sustained slight degradation |
| 23 | S-si-d | Sustained significant degradation |
| 24 | U-t | Uncertain trend |

### *2.3. Research Methods*

#### 2.3.1. Pixel Dichotomy Model

The pixel dichotomy model, a remote sensing image analysis method, classifies pixels into vegetation and non-vegetation. A significant correlation exists between vegetation coverage and NDVI, facilitating the direct extraction of vegetation coverage information by establishing a conversion relationship. This study applies the pixel dichotomy method to calculate vegetation coverage [13]. The calculation formula for vegetation coverage is as follows:

$$FVC = (NDVI - NDVI_s)/(NDVI_v - NDVI_s) \quad (1)$$

In this formula, $FVC$ represents fractional vegetation cover, $NDVI_s$ is the $NDVI$ value of a pixel without vegetation cover, and $NDVI_v$ represents the $NDVI$ for a fully vegetated pixel. Theoretical $NDVI$ values for non-vegetated and fully vegetated pixels are approximately 0 and 1, respectively, although these values may vary with atmospheric conditions, vegetation types, and other factors.

To examine the spatiotemporal evolution of vegetation cover in the Loess Plateau, vegetation coverage was classified into five levels: low (L, $FVC \leq 30\%$), medium-low (ML, $30\% < FVC \leq 45\%$), medium (M, $45\% < FVC \leq 60\%$), medium-high (MH, $60\% < FVC \leq 75\%$), and high (H, $FVC > 75\%$), providing vegetation coverage data for the study area from 2000 to 2022.

#### 2.3.2. Trend Analysis

To assess the spatiotemporal trends and their significance in vegetation coverage in the Loess Plateau from 2000 to 2022, this study integrates Theil–Sen Median trend analysis with the Mann–Kendall significance test [31]. The formula for Theil–Sen Median trend analysis is as follows:

$$S_{FVC} = median\left(\frac{FVC_j - FVC_i}{j - i}\right), 2000 \leq i < j \leq 2022 \quad (2)$$

Here, $S_{FVC}$ represents the vegetation coverage trend. $S_{FVC} > 0$ denotes an increasing trend, $S_{FVC} < 0$ a decreasing trend, and $S_{FVC} = 0$ indicates stability. The absolute value of $S_{FVC}$ reflects the magnitude of change in vegetation coverage, with $FVC_j$ and $FVC_i$ representing vegetation coverage in years $j$ and $i$, respectively.

The Mann–Kendall significance test is given by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(FVC_j - FVC_i) \quad (3)$$

where $n$ is the length of the time series, which is 23 in this study. The sign function $sgn$ ( ) is defined as:

$$sgn(FVC_j - FVC_i) = \begin{cases} 1, (FVC_j - FVC_i) > 0 \\ 0, (FVC_j - FVC_i) = 0 \\ -1, (FVC_j - FVC_i) < 0 \end{cases} \quad (4)$$

The Z-statistic is used for trend testing:

$$Z = \begin{cases} \frac{S-1}{\sqrt{var(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{var(S)}} & S < 0 \end{cases} \quad (5)$$

$$var(S) = \frac{n(n-1)(2n+5)}{18} \quad (6)$$

The significance of the trend is tested at a given significance level $\alpha$ (usually 0.05). If $|Z| > Z_{1-\alpha/2}$, it indicates a significant change in the time series. The combination of Theil–Sen Median trend analysis and Mann–Kendall significance test is used to classify the types of vegetation coverage changes in the Loess Plateau, as shown in Table 2.

**Table 2.** Classification of vegetation coverage change trend types.

| $S_{FVC}$ | Z Value | Trend of FVC |
|---|---|---|
| ≥0.0005 | ≥1.96 | Significant improvement |
| ≥0.0005 | −1.96–1.96 | Slightly improvement |
| −0.0005–0.0005 | −1.96–1.96 | Basically unchanged |
| <−0.0005 | −1.96–1.96 | Slightly degradation |
| <−0.0005 | ≤−1.96 | Significant degradation |

#### 2.3.3. Sustainability Analysis

The Hurst exponent serves as a critical indicator for assessing long-term correlation and the sustainability of time-series data. Calculated via the R/S analysis method, the Hurst exponent ranges from 0 and 1. When 0 < Hurst < 0.5, it signifies a negative correlation, indicating that future trends will likely opposite past trends. When Hurst = 0.5, the time series is random, suggesting no clear dependence between future and past trends. When 0.5 < Hurst < 1, it signifies a positive correlation, implying that future trends are aligned with past trends [32]. A Hurst exponent closer to 1 indicates a stronger positive correlation; while values nearer to 0 indicate a stronger negative correlation. This characteristic can be applied to predict future *FVC* trends over a specific period.

## 3. Results

### *3.1. Temporal Variation Characteristics of Vegetation Coverage in the Loess Plateau*

Figure 2 illustrates the temporal variations in the annual average vegetation coverage of the Loess Plateau from 2000 to 2022. During the 23-year period, annual average vegetation coverage displayed an overall upward trend, increasing from 0.439 in 2000 to 0.636 in 2022, with an annual growth rate of 0.86% ($R^2$ = 0.903, $p$ < 0.01). From 2000 to 2013, annual average vegetation coverage fluctuated between 0.423 and 0.583, growing at an annual rate of 0.80% ($R^2$ = 0.742, $p$ < 0.01), with a multi-year average of 48.67%, classifying it in the

medium coverage level. From 2014 to 2022, annual average vegetation coverage continued to rise at an annual rate of 0.82% ($R^2$ = 0.596, $p < 0.01$), reaching a medium-high coverage level by 2020.

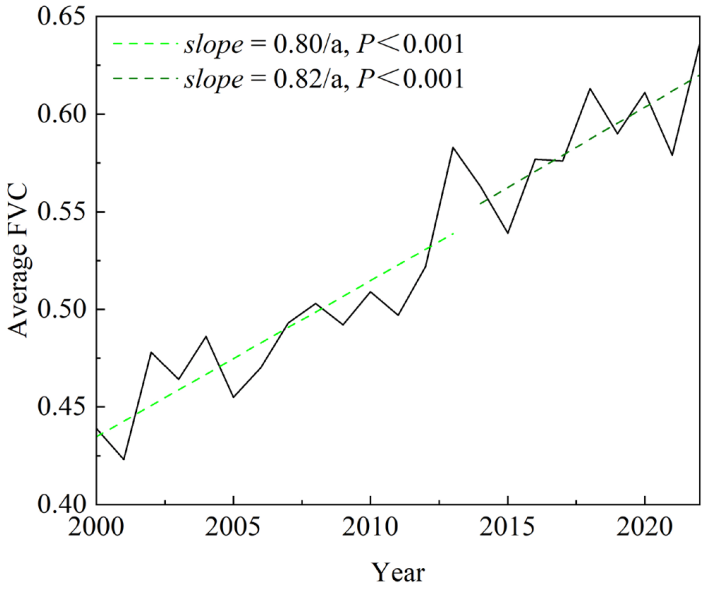



**Figure 2.** Annual variation trend of average FVC from 2000 to 2022. The light-green dashed line in the figure represents the change trend of the annual average vegetation coverage from 2000 to 2013, while the dark green dashed line indicates the change trend of that from 2014 to 2022.

An analysis of temporal variations in different vegetation coverage levels (Figure 3) reveals a clear decreasing trend in areas with low, medium-low, and medium vegetation coverage in the Loess Plateau. Specifically, low coverage areas declined by 149 × $10^3$ $km^2$ (22.83%) from 2000 to 2022, with a fluctuating decrease at a rate of 6.297 × $10^3$ $km^2$ per year ($p < 0.001$). Likewise, medium-low coverage areas decreased by 35 × $10^3$ $km^2$ (5.34%), with a fluctuating decline at a rate of 1.910 × $10^3$ $km^2$ per year ($p < 0.001$). The reduction in medium coverage areas was minor, decreasing by only around 10 × $10^3$ $km^2$ (1.52%), with a weaker trend declining at a rate of 0.529 × $10^3$ $km^2$ per year ($p < 0.001$).

In contrast, medium-high and high vegetation coverage areas showed significant increases, reflecting substantial vegetation recovery. Medium-high coverage areas grew by approximately 21 × $10^3$ $km^2$ (3.20%) from 2000 to 2022, with a fluctuating increase at a rate of 1.310 × $10^3$ $km^2$ per year ($p < 0.001$). Over the 23-year period, high coverage areas showed a remarkable upward trend, expanding at a rate of 7.427 × $10^3$ $km^2$ per year ($p < 0.001$), with a total increase of 173 × $10^3$ $km^2$ (26.49%). These results suggest that the primary trends in vegetation coverage levels in the Loess Plateau include an increase in high coverage (26.49%) and a decrease in low coverage (22.83%).

### *3.2. Spatiotemporal Evolution of Vegetation Coverage in the Loess Plateau*

To examine the spatiotemporal evolution of vegetation coverage, the years 2000, 2013, and 2022 were chosen based on temporal variation characteristics (Figure 4). In terms of spatial pattern changes, vegetation coverage in the Loess Plateau showed a gradual increase from the southeast to the northwest, marked by a steady decrease in low coverage areas and a growth in high-coverage area. Specifically, vegetation coverage expanded northwestward along the "Datong—Shuozhou—Lishi—Yan'an—Xifeng—Pingliang—Tianshui" line in 2000, advancing to the "Baotou—Dongsheng—Yulin—Lanzhou—Xining" line by 2022, leaving only northern areas along this line for further ecological engineering implementation.

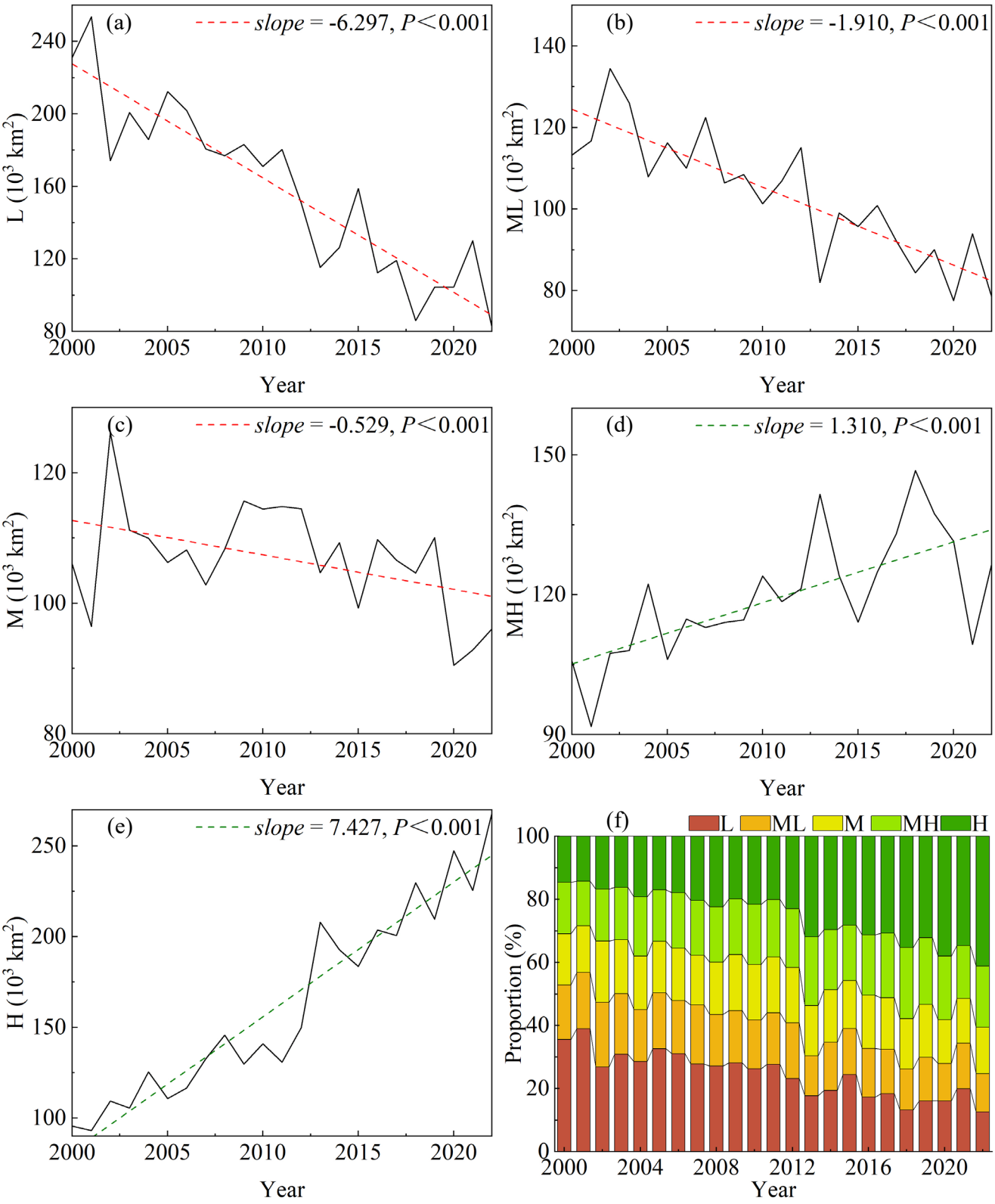



**Figure 3.** Annual variation trends of different vegetation coverage levels from 2000 to 2022. (**a**–**c**) show the area changes in low, medium-low, and medium vegetation coverage, respectively, with the red dashed lines indicating a decreasing trend in area. (**d**,**e**) illustrate the area changes in medium-high and high vegetation coverage, with the green dashed lines representing an increasing trend in area. (**f**) displays the change in the area proportion of different vegetation coverage levels.

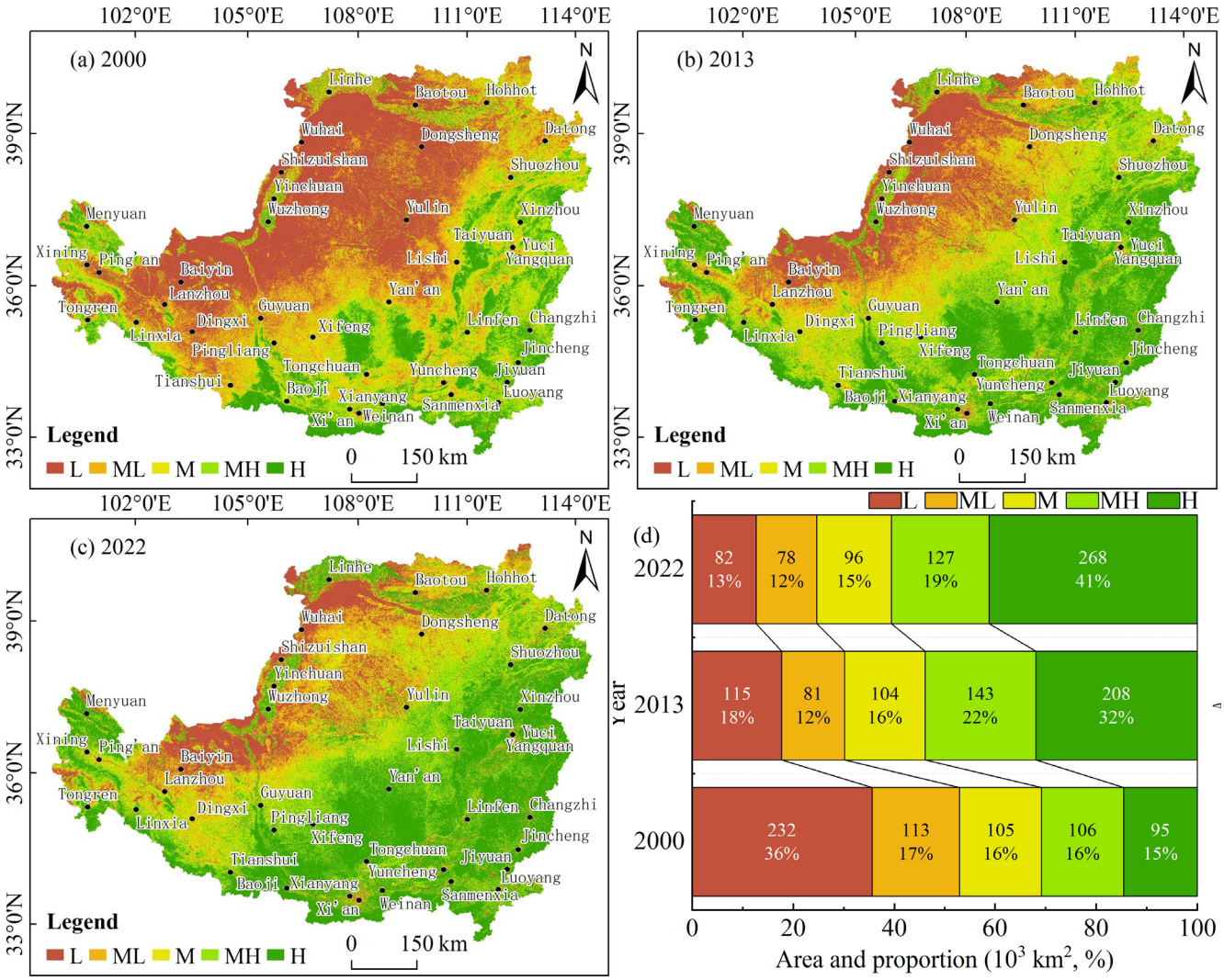



**Figure 4.** Spatial evolution of vegetation coverage levels in the Loess Plateau. (**a**–**c**) depict the spatial distribution of vegetation coverage levels in the Loess Plateau for the years 2000, 2013, and 2022, respectively. (**d**) illustrates the area and proportion of each vegetation coverage level in 2000, 2013, and 2022.

In 2000, low-coverage areas dominated vegetation coverage levels, comprising 36% of the total area and covering approximately 232 × $10^3$ km$^2$. High-coverage vegetation areas covered only about 95 × $10^3$ km$^2$, accounting for 15% of the total area. By 2013, high coverage areas had become predominant, accounting for 32% of the total area with a coverage of 208 × $10^3$ km$^2$, while low coverage decreased to 115 × $10^3$ km$^2$. In 2022, high coverage remained dominant, covering 41% (268 × $10^3$ km$^2$) of the total area, with low coverage reduced to around 82 × $10^3$ km$^2$.

In terms of vegetation coverage transitions (Figure 5), between 2000 and 2013, 61.12% (approximately 400 × $10^3$ km$^2$) of the vegetation coverage levels in the study area transitioned. Primary transitions included shifts from low to medium-low coverage (9.07%), low to medium-high coverage (6.46%), medium-low to medium coverage (6.01%), medium-low to medium-high coverage (6.47%), medium to medium-high coverage (7.65%), medium to high coverage (4.88%), and medium-high to high coverage (11.03%). From 2013 to 2022, 41.03% (approximately 270 × $10^3$ km$^2$) of vegetation coverage levels in the Loess Plateau transitioned. The main transitions included shifts from low to medium-low coverage (4.89%), from medium-low to medium coverage (4.45%), from medium to medium-high coverage (6.09%), and from medium-high to high coverage (9.50%). These findings sug-

gest that over the past 23 years, vegetation coverage in the Loess Plateau has demonstrated a positive trend, with the transitions mainly reflecting a shift from lower to higher coverage levels.

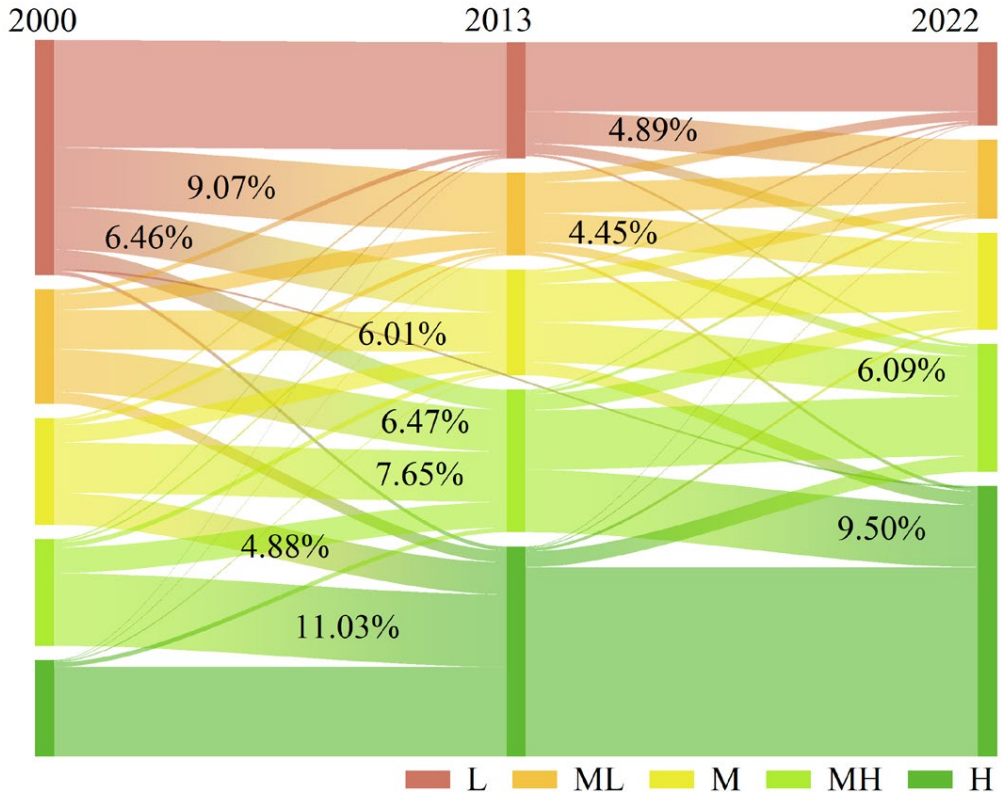



**Figure 5.** Transitions of vegetation coverage levels in different periods in the Loess Plateau.

### *3.3. Spatiotemporal Trends and Sustainability Analysis of Vegetation Coverage in the Loess Plateau*

Using the Theil–Sen Median trend classification and the Mann–Kendall significance test at the 30 m pixel scale, the spatial distribution of vegetation coverage trends in the Loess Plateau from 2000 to 2022 was mapped (Figure 6). Overall, vegetation coverage in the Loess Plateau exhibited a significant improvement trend, with 93% of the study area showing positive change. Specifically, areas with significant improvement covered approximately $530 \times 10^3$ km$^2$ (80%), while slightly improved areas covered about $87 \times 10^3$ km$^2$ (13%). The slightly improved areas were mainly concentrated in the regions around Wuhai, Shizuishan, Yinchuan, and Wuzhong, as well as parts of Baotou and Baiyin. Conversely, degraded vegetation coverage spanned around $31 \times 10^3$ km$^2$ (5%), primarily distributed along the Baoji to Xianyang to Xi'an to Yuncheng, from Luoyang to Jiyuan to Changzhi, and from the Wuzhong to Linhe to the Hohhot lines along the Yellow River Basin. The area with stable vegetation coverage, which remained unchanged, was approximately $11 \times 10^3$ km$^2$ (2%), scattered throughout the study area.

The Hurst exponent for vegetation coverage in the Loess Plateau from 2000 to 2022 ranged from 0.12 to 0.77, with an average value of 0.65. Areas with a Hurst exponent above 0.5 comprised 96% of the study area, suggesting that most regions exhibit positive sustainability. This suggests that areas showing an improving trend in vegetation coverage far outweigh those showing degradation. Coupling the Hurst exponent sustainability assessment with spatiotemporal trend classifications, six potential future scenarios for vegetation development in the Loess Plateau were identified. These scenarios include sustained significant improvement (S-si-i), sustained slight improvement (S-sl-i), sustained stability (S-s), sustained slight degradation (S-sl-d), sustained significant degradation (S-si-d), and uncertain trend (U-t). Approximately $588 \times 10^3$ km$^2$ (90%) of the Loess Plateau is expected

to demonstrate sustained improvement trend in vegetation coverage, with 80% showing significant improvement and 10% showing slight improvement. About 29 × $10^3$ $km^2$ (5%) of the area is expected to experience sustained degradation, still distributed along the Baoji–Xianyang–Xi'an–Yuncheng line, the Luoyang–Jiyuan–Changzhi line, and the Wuzhong–Linhe–Hohhot line along the Yellow River Basin. The area with stable and unchanged vegetation coverage is estimated to be about 7 × $10^3$ $km^2$ (1%), while the area with uncertain vegetation coverage trends is approximately 28 × $10^3$ $km^2$ (4%), mainly concentrated in parts of Wuhai, Baiyin, and Xianyang.

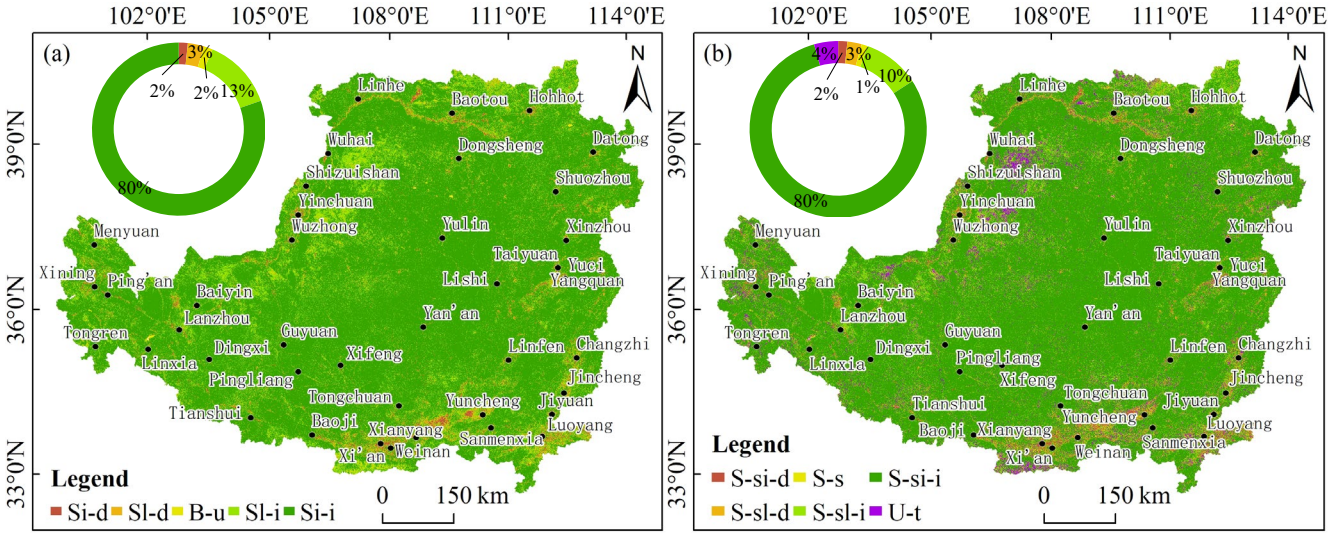



**Figure 6.** Spatiotemporal trends (**a**) and sustainability (**b**) of vegetation coverage in the Loess Plateau from 2000 to 2022.

### *3.4. Impact of the GGP on the Spatiotemporal Changes in Vegetation Coverage*

In areas influenced by the GGP, a significant increasing trend is observed in high and medium-high vegetation coverage levels, while low and medium-low coverage levels show a marked decrease (Figure 7). Specifically, high vegetation coverage expanded by around 11 × $10^3$ $km^2$ from 2000 to 2022, at an annual rate of 0.456 × $10^3$ $km^2$ ($p < 0.001$). Medium-high vegetation coverage similarly increased by 103% over this period, adding approximately 11 × $10^3$ $km^2$ at a rate of 0.304 × $10^3$ $km^2$ per year ($p < 0.001$). In contrast, medium coverage fluctuated between 7.327 × $10^3$ $km^2$ and 13.110 × $10^3$ $km^2$, with no significant trend detected ($p > 0.05$). Meanwhile, medium-low and low vegetation coverage areas exhibited significant declines, decreasing at rates of 0.387 × $10^3$ $km^2$ per year ($p < 0.001$) and 0.430 × $10^3$ $km^2$ per year ($p < 0.001$), respectively, with a total reduction of approximately 17 × $10^3$ $km^2$ from 2000 to 2022.

In terms of vegetation coverage transitions, 81.67% of regions experienced changes, with 74.47% of the coverage levels shifting upward. Specifically, low coverage primarily shifted to medium-low, medium, and medium-high levels, accounting for 22.43% (9.589 × $10^3$ $km^2$) of the area. Medium-low coverage primarily shifted to medium-high and medium levels, covering 19.04% (8.139 × $10^3$ $km^2$) of the area. Medium coverage largely transitioned to high and medium-high levels, accounting for 15.69% (6.706 × $10^3$ $km^2$) of the area. Medium-high coverage predominantly shifted to high coverage, covering 9.38% (4.010 × $10^3$ $km^2$) of the area.

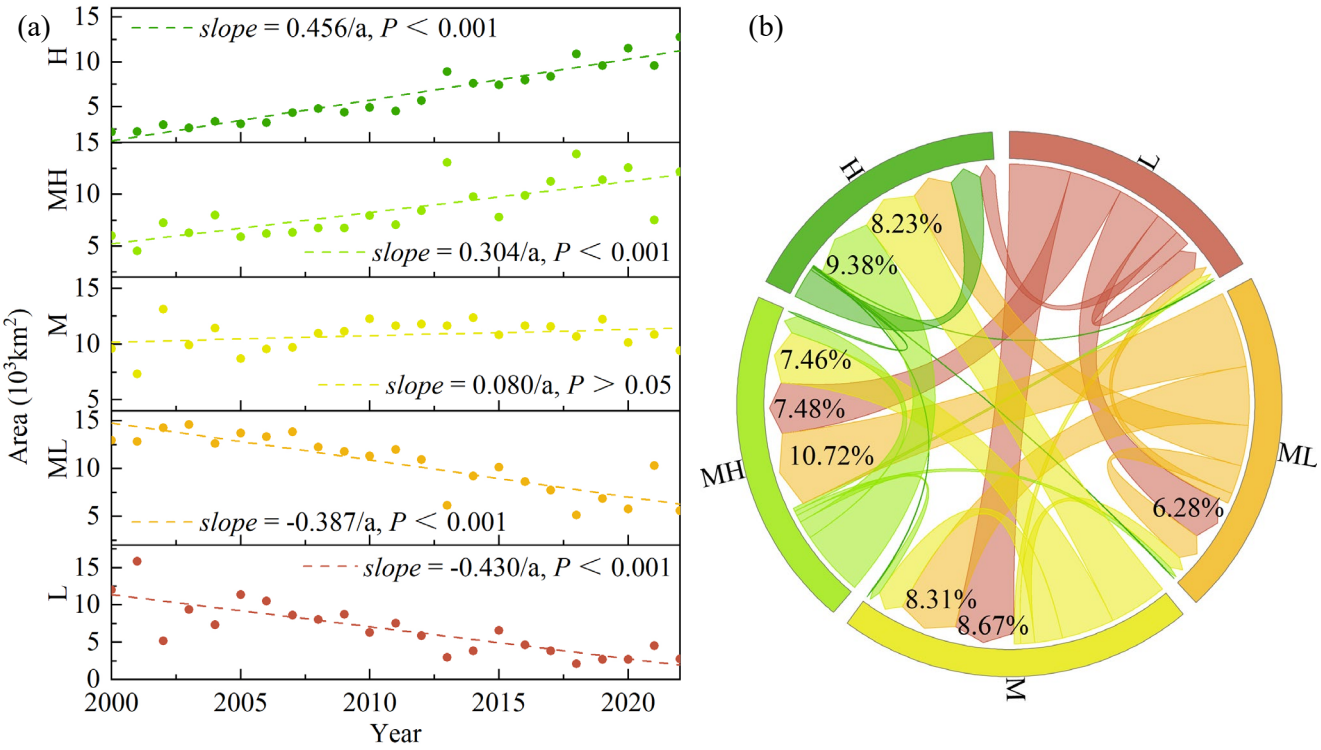



**Figure 7.** Temporal changes and transitions of vegetation coverage levels in the GGP area. (**a**) presents the trend in area changes for different levels of vegetation coverage in regions affected by the GGP. (**b**) shows the area proportions of vegetation coverage conversion of different levels before and after the implementation of the GGP.

## 4. Discussion

### *4.1. Comparative Analysis with Related Studies*

This study utilized long-term, medium-to-high spatial resolution Landsat NDVI data, finding an improving trend in vegetation coverage in the Loess Plateau from 2000 to 2022, with an annual growth rate of 0.86%. This rate is higher than the NDVI growth trend of 0.75% per year from 2000 to 2020 reported by Zhang et al. [33] and the 0.538% per year increase reported by Gou et al. [34]. Some studies, however, suggest a decline in vegetation coverage after 2015 [35]. In our study, 93% of the Loess Plateau showed vegetation coverage improvement from 2000 to 2022, similar to the 92.67% reported by Zhang et al. [33]. Vegetation coverage generally increased from northwest to southeast [36], reflecting a gradient from low to high vegetation that aligns with precipitation and temperature distribution [37,38]. The most significant period of vegetation improvement occurred between 2011 and 2013, with regions showing positive changes expanding northwestward. By contrast, other studies indicated a distinct greening pattern beginning in the central Loess Plateau between 2006 and 2008, later extending to the eastern and southwestern regions [39]. Additionally, some research suggests that vegetation recovery potential reached a turning point in 2010, shifting from growth to decline [3].

The Chinese government has enacted various policies for ecological protection and restoration, encouraging researchers to examine vegetation recovery responses using geospatial analysis and statistical methods. In the Mu Us Sandy Land, a representative region for artificial vegetation restoration, an analysis using the artificial vegetation restoration suitability index revealed a restoration rate of 264.11 km$^2$ per year, demonstrating the spatiotemporal process of vegetation recovery in this area [40]. For example, ecological policies in Qinghai Province have significantly enhanced vegetation coverage and positively influenced the environment [41]. The adoption of the Yangtze River "1515" shoreline zoning control plan has made vegetation coverage along the Yangtze River a key

focus for restoration [42]. The GGP, initiated in 1999 to combat soil erosion in the Three Gorges Reservoir Area, is projected to play an increasingly vital role in future erosion control [43]. In the Wenchuan earthquake core zone, MODIS vegetation coverage data from the past decade indicate a recovery rate of approximately 90% in the disaster area [44]. The degree of vegetation damage and cover rate are significantly correlated with proximity to urban areas and topographic factors. Vegetation recovery is strongly influenced by human activity, showing a recovery rate of approximately 0.99, which is inversely correlated with altitude, with recovery rates varying across slope gradients [45]. By contrast, this study quantitatively analyzes spatiotemporal trends in vegetation cover in the Loess Plateau under the GGP, highlighting the effectiveness of vegetation recovery over the past 23 years.

In determining vegetation recovery, this study integrates the Theil–Sen Median and Mann–Kendall significance tests, defining five vegetation recovery categories—significant improvement, slight improvement, stability, slight degradation, and significant degradation based on slope and significance thresholds. This method provides a robust foundation for evaluating vegetation recovery effectiveness in the Loess Plateau. In contrast, other researchers have primarily used two methods for assessing vegetation recovery, listed as follows: (1) using simple linear regression to detect pixel-level slope changes, where a positive slope indicate recovery and negative slope indicate degradation [46]; (2) measuring vegetation expansion, where an increase in vegetation area signifies recovery and a decrease indicates degradation [28]. Clearly, the integrated approach in this study, combining slope and significance based on long-term vegetation coverage data, offers a more scientifically robust method for identifying vegetation recovery status.

### 4.2. Influence of Human Activities and Natural Environmental Factors on Vegetation Coverage

Spatiotemporal variations in vegetation coverage in the Loess Plateau are significantly shaped by human activities and environmental factors [47]. Human activity intensity across regions shows a strong correlation with vegetation cover. High-intensity human activities result in sharp declines in vegetation coverage, whereas initiatives like the GGP effectively mitigate vegetation degradation [48]. Over the past 40 years, increases in vegetation coverage have been closely linked to ecological engineering efforts [49]. For instance, a strong correlation exists between cumulative afforestation and vegetation indices in Yan'an and Yulin [50]. Approximately 58.19% of grassland and 25.32% of cropland in this region have been converted to forest, demonstrating significant vegetation recovery [20,51]. In the Loess Plateau, areas with degraded vegetation are predominantly found in urban centers, surrounding areas, wastelands, and bare land [28].

Among natural environmental factors, temperature, precipitation, vegetation type, and soil type play crucial roles in determining vegetation coverage. Temperature is significantly positively correlated with vegetation in the central and southeastern Loess Plateau [52]. Annual precipitation strongly influences vegetation [33], with increased rainfall in ecologically restored areas positively impacting vegetation recovery [53]. Additionally, topographical changes influence vegetation coverage distribution, with lower coverage levels shifting to higher altitudes and higher coverage levels moving to lower altitudes [54]. In the Loess Plateau, human activities remain the primary driver of vegetation changes, although the impact of natural environmental factors on vegetation has gradually increased [24,55].

### 4.3. Limitations and Future Studies

This study has several limitations. The 30 m NDVI dataset is derived from Landsat-5, Landsat-7, Landsat-8, and Landsat-9 satellite images; however, differences in band numbers, spatial and temporal resolutions, and sensor enhancements across these satellites, introduce uncertainties in NDVI calculation and analysis. The classification of vegetation recovery types using $S_{FVC}$ and $Z$ values could benefit from refinement through the integration of ground survey data. Additionally, applying the Braun-Blanquet method in future studies could offer valuable insights into the spatiotemporal dynamics of vegetation community structure and compositional classification during the restoration process [56]. Remote

sensing images vary in spatial and temporal resolutions and quality. Thus, future studies could perform comprehensive comparative analyses of vegetation coverage trends at small, medium, and large scales. Although the GGP has promoted vegetation recovery in the Loess Plateau, large-scale afforestation may ultimately contribute to water scarcity in northern China [57]. Ensuring sustainable ecological restoration alongside effective water resource management in the Loess Plateau remains a critical focus for future research [58].

## 5. Conclusions

From 2000 to 2022, vegetation coverage in the Loess Plateau rose from 0.439 to 0.636, with coverage levels shifting from medium to medium-high. Over time, areas with low, medium-low, and medium coverage levels decreased, while medium-high and high coverage areas expanded, indicating a positive overall trend in vegetation coverage. The spatial progression of vegetation coverage in the Loess Plateau shows a gradual increase from southeast to northwest. Initially dominated by low coverage in 2000, the region transitioned to predominantly high coverage by 2022, with low coverage areas decreasing and high coverage areas expanding, reflecting an upward shift in coverage levels. A positive trend in vegetation coverage was observed in 93% of the Loess Plateau, with only 5% of the areas showing degradation. Areas experiencing vegetation degradation are primarily concentrated in rapidly urbanizing regions and along the Yellow River Basin. In the future, 96% of the vegetation cover in the Loess Plateau is expected to maintain positive sustainability, with 90% showing a sustained improvement trend. In areas influenced by the GGP, high and medium-high vegetation coverage levels show a marked increasing trend, while low and medium-low coverage levels exhibit a significant decline. Approximately 81.67% of the region underwent changes in vegetation coverage levels, with 74.47% transitioning to higher levels.

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